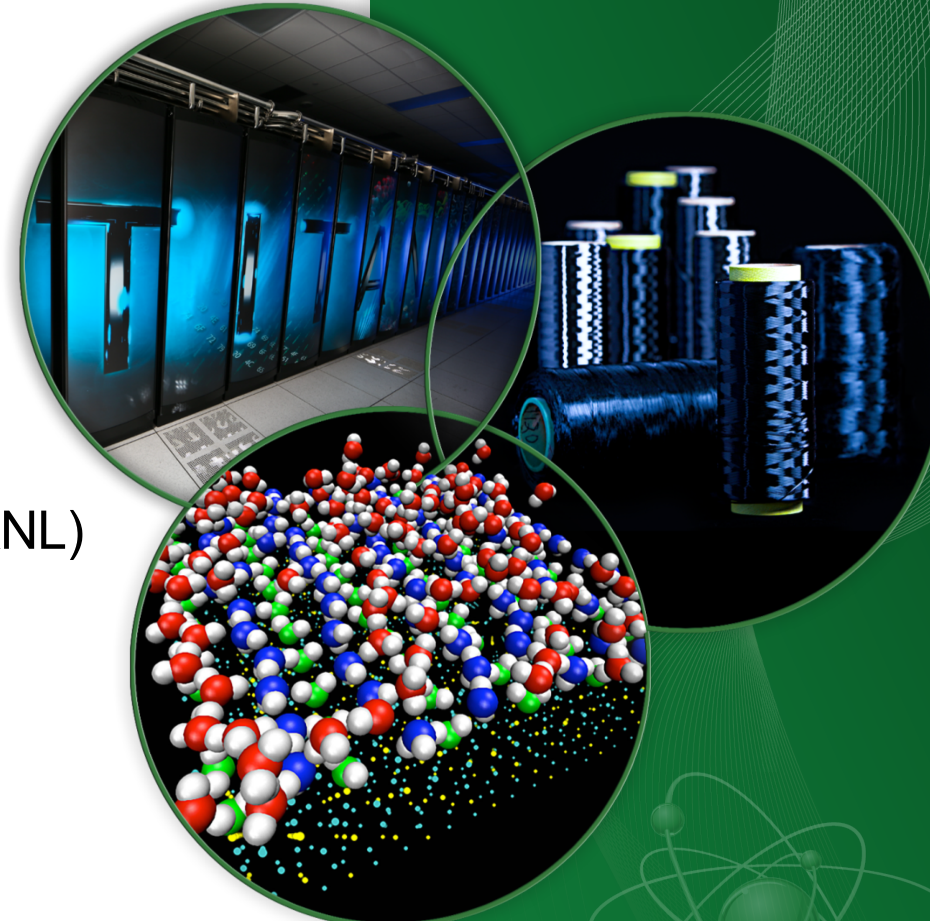
Improvements for the ^{63}Cu and ^{65}Cu Resonance Evaluations for Criticality Safety Applications



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Overview of Major Accomplishments in the Resolved Resonance Region Evaluation of ^{63}Cu and ^{65}Cu

1. Experimental thermal cross section measurement
2. Resolved resonance region extended 3 x
3. Experimental capture data analyzed
4. High fidelity angular distribution generated

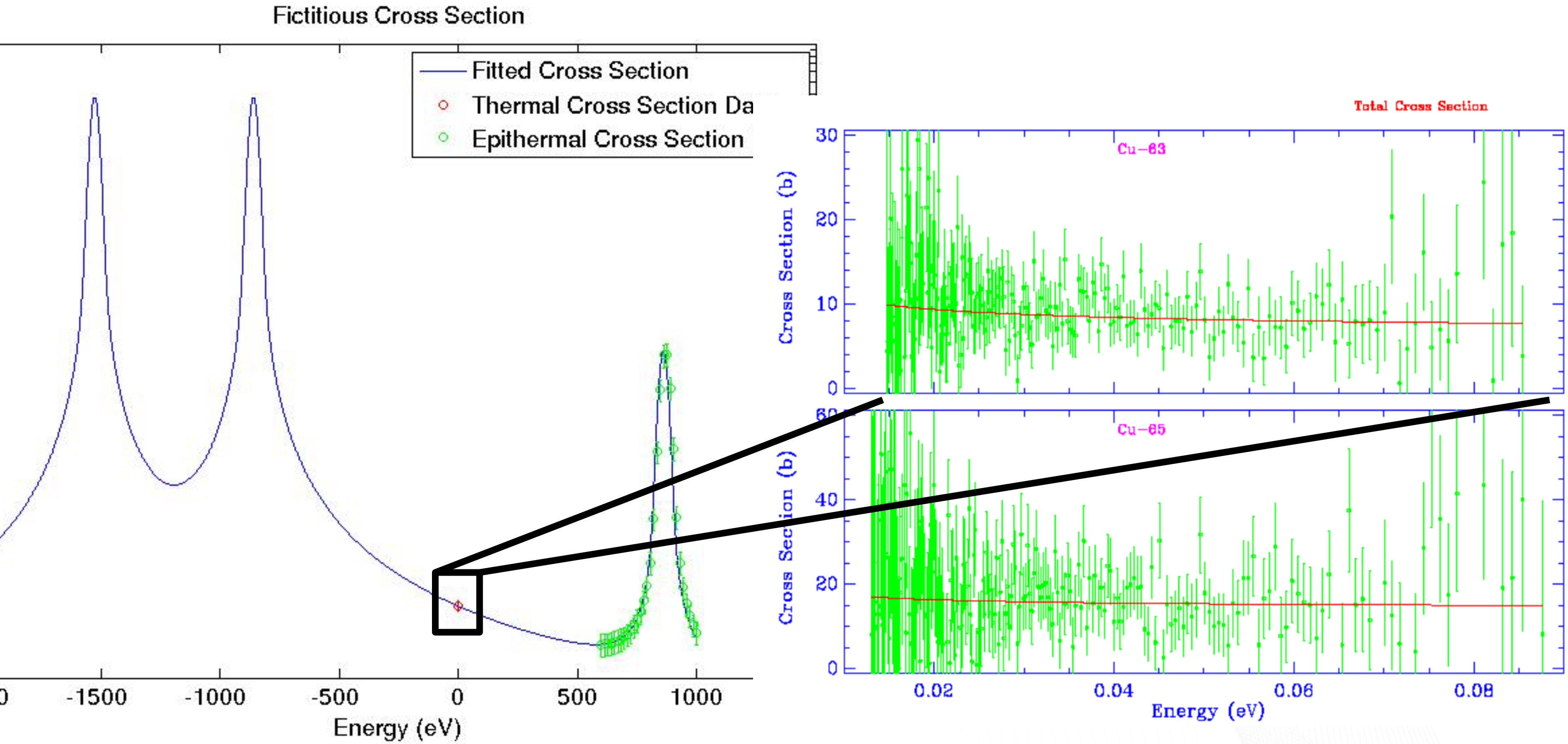
SAMMY: Computer Code for R-Matrix Analysis

- Originally developed by ORNL to evaluate data from the ORELA experimental facility
- Currently used world wide for analysis of experimental cross section data
- Based on R-Matrix theory of nuclear reactions
- Uses Bayes's method (generalized least squares) to find optimal parameter values
- Generates uncertainty data for resonance region via Bayesian update method

Experimental Data used in the New Evaluation

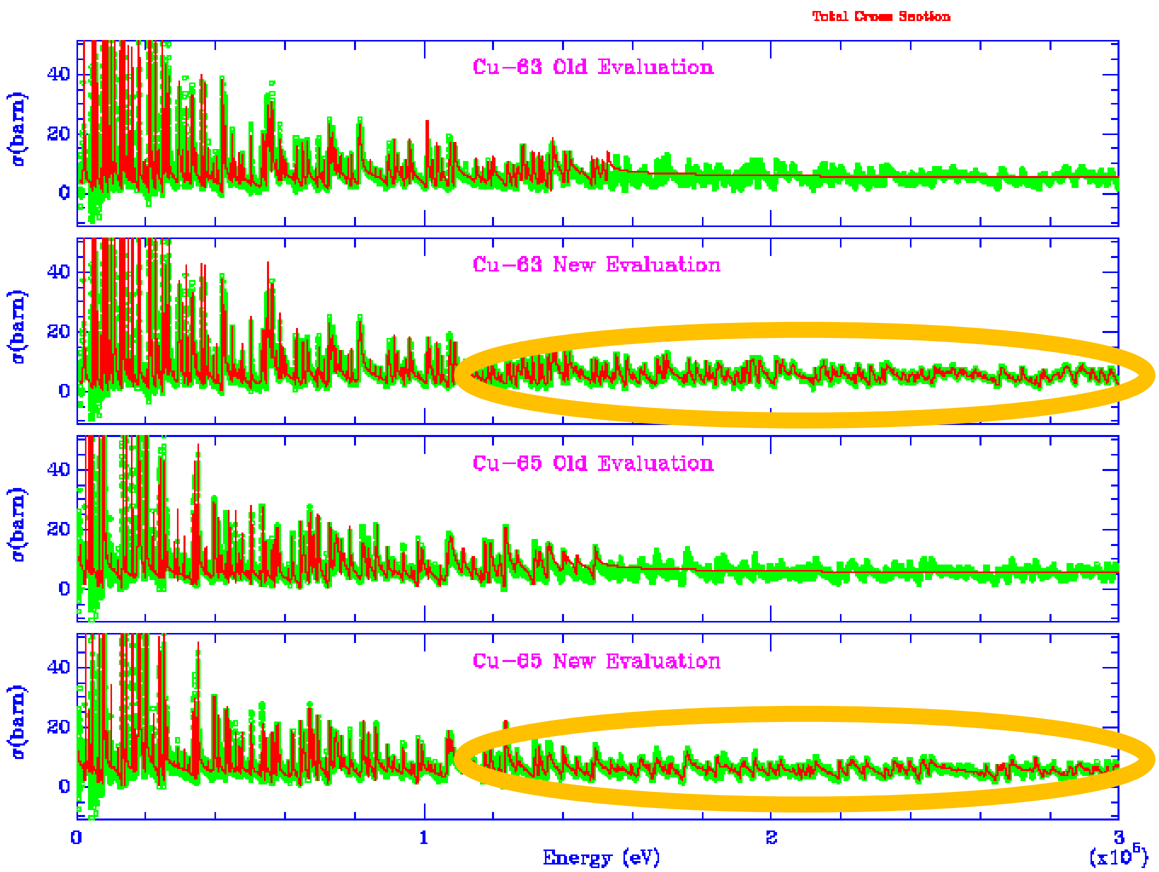
Reference	Energy Range (eV)	Facility	Measurement
Pandey et al.	32 – 185 000	ORELA	Trans. at 78 m
Pandey et al.	1 000 – 1 400 000	ORELA	Trans. at 78 m
Guber et al.	100 – 90 000	GELINA	Cap. at 58 m
Guber et al.	100 – 2 200 272	GELINA	Cap. at 58 m
Sobes et al.	0.01 – 0.1	MITR	Trans. at 1.2 m

Thermal Cross Section Measurement to Define External Levels



Much more definition of the negative external levels if we fit a differential cross section

Extending the Resolved Resonance Region (Total Cross Section)



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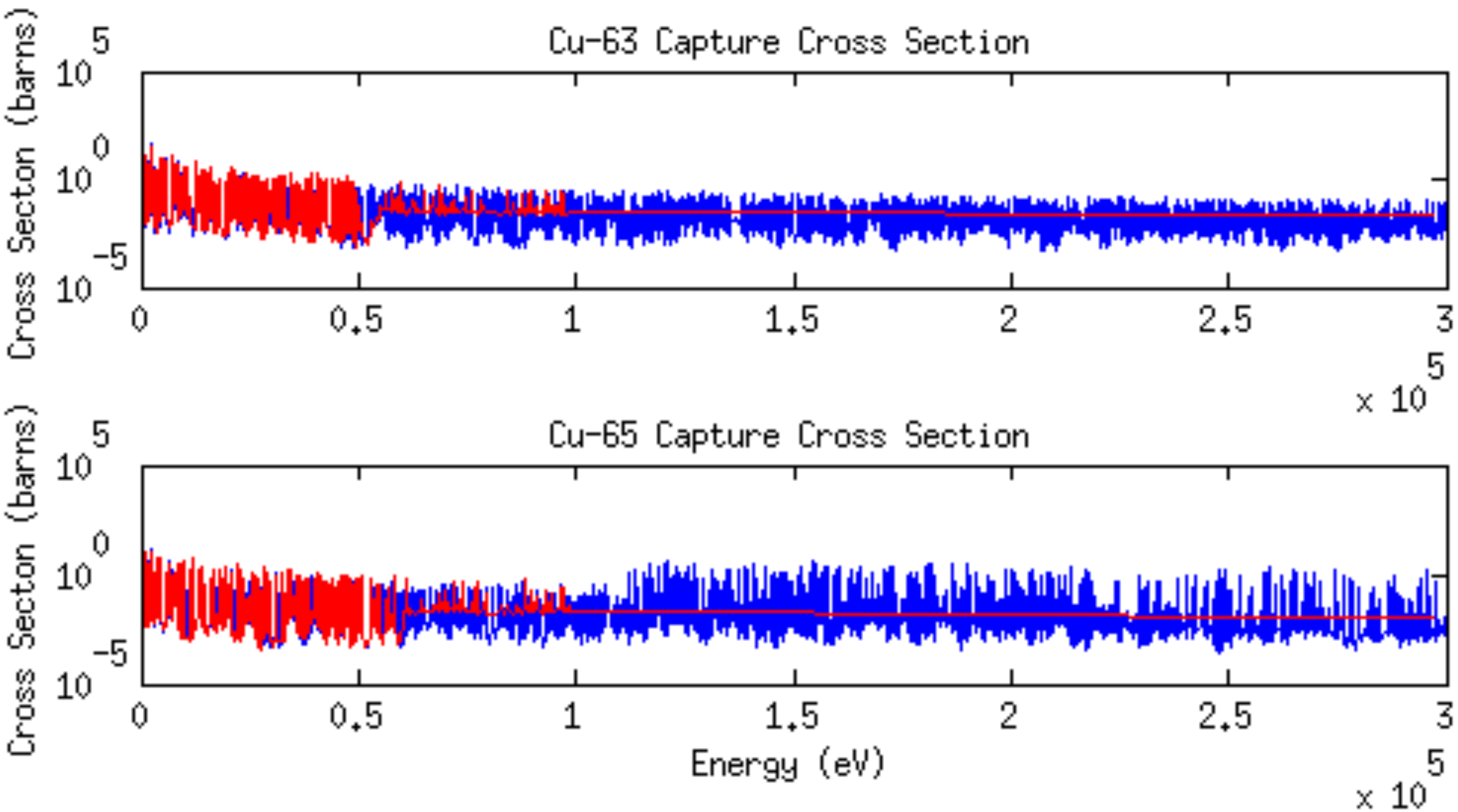
Extending the Resolved Resonance Region (Capture Cross Section)



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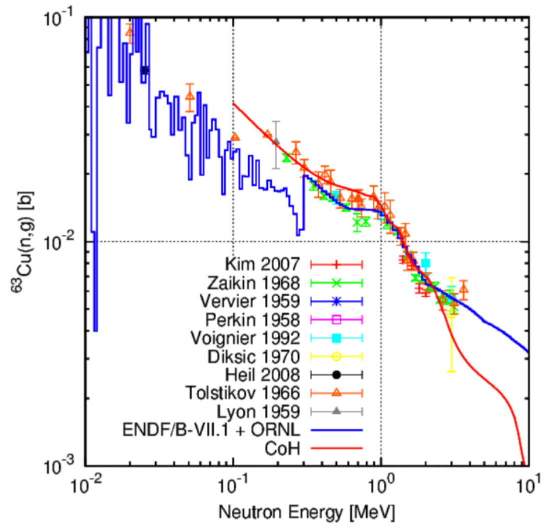
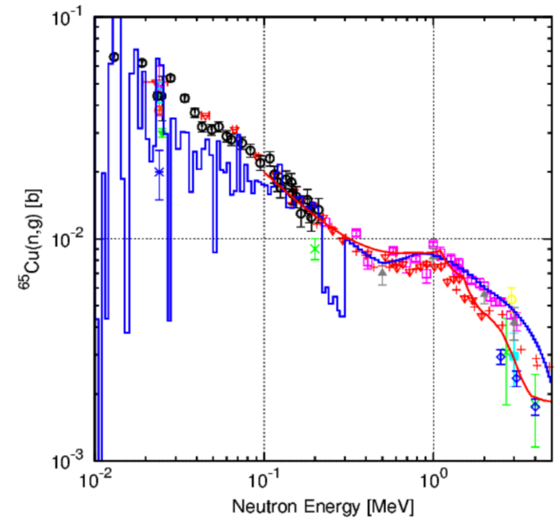
Updated Resolved Resonance Region Evaluation: Updated Capture Cross Section E > 220 keV

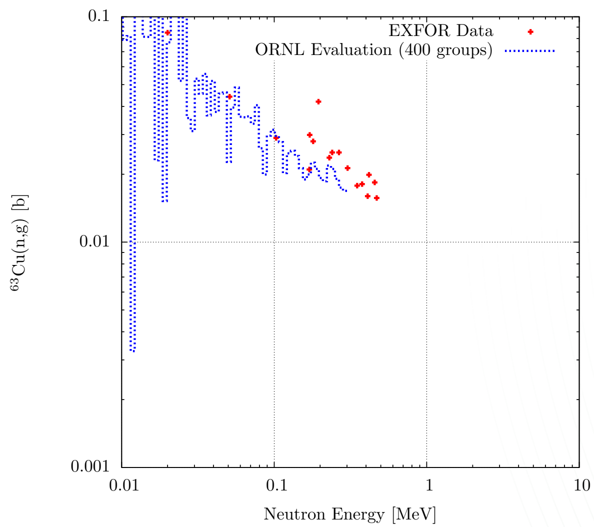
- From Dr. Kawano, Mini CSEWG 2015



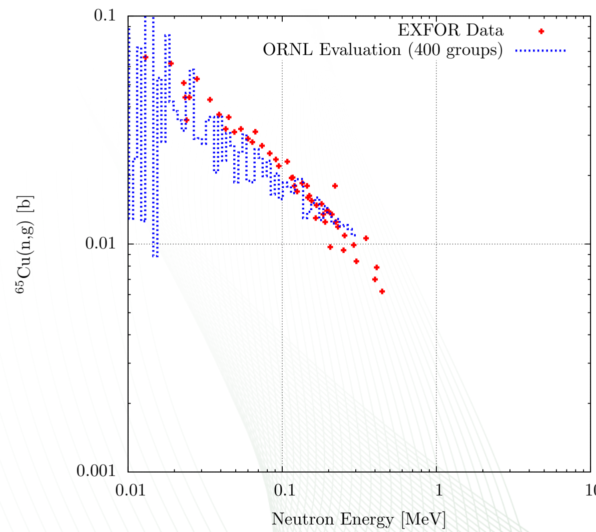


- Corrected capture cross sections (in rev. 620 and 622 above 220 keV cross sections were underestimated)

^{63}Cu Capture Cross Section vs. Integral Measurements



^{65}Cu Capture Cross Section vs. Integral Measurements



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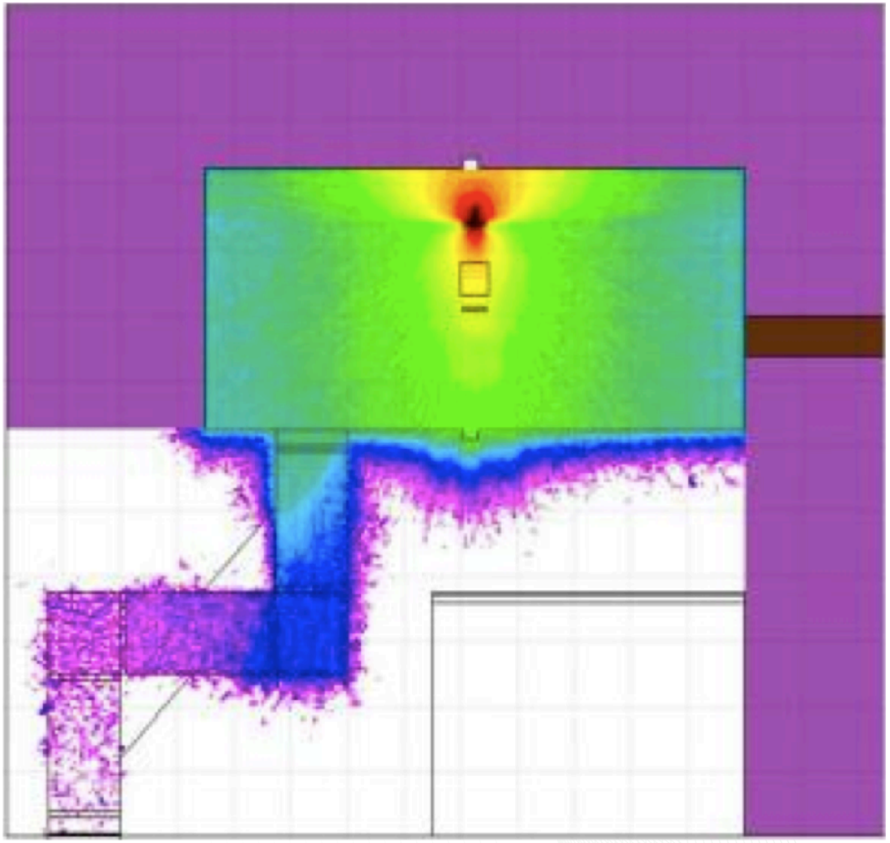
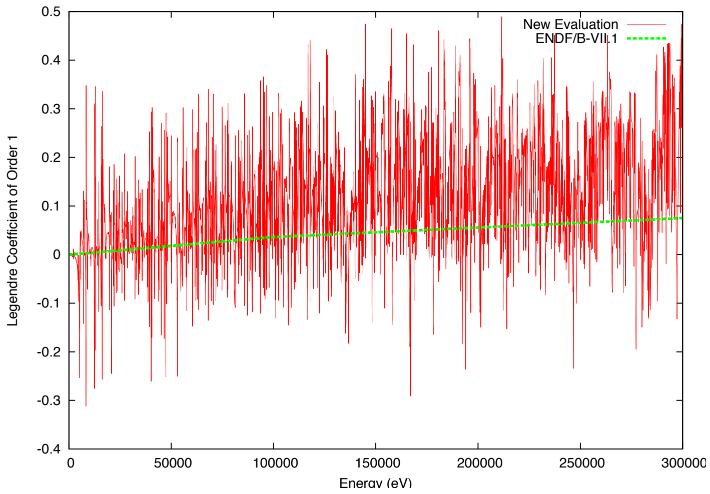
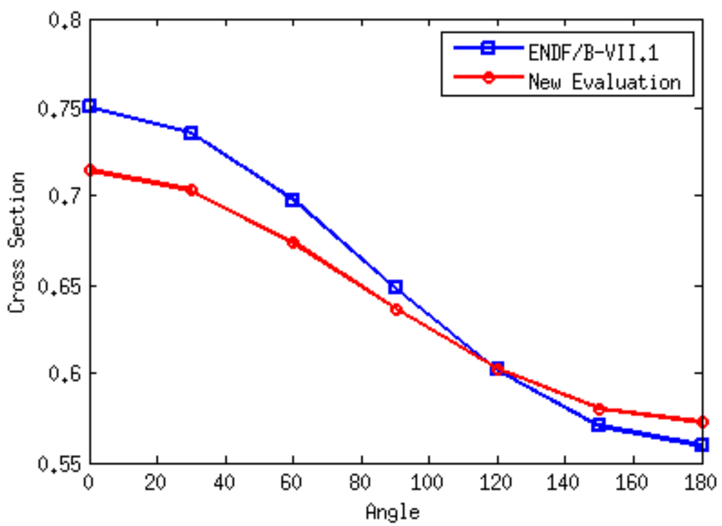
Importance of Angular Distributions

- For radiation transport calculations, it can be crucially important to correctly understand which direction neutrons are more likely to travel after a scattering event
- NCS example:
  Analysis of criticality accident alarm system (CAAS) detector placement



High Fidelity Model of Angular Distributions





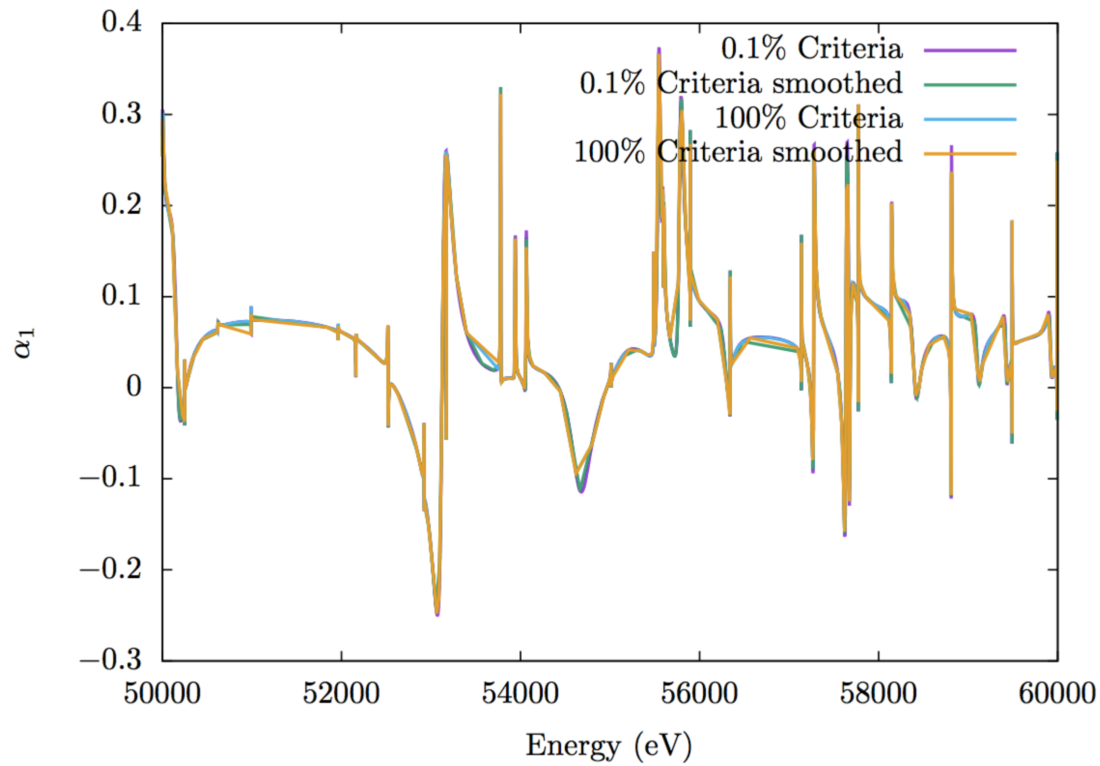
Differential cross section with respect to angle at E=60 keV for 63 Cu(n,els)

- Angular distributions display physical resonances
- The average treatment leads to inconsistency between angle integrated cross sections and angular distributions

$$\alpha_l(E) = \frac{2\pi}{\sigma_s(E)} \int_{-1}^{+1} \sigma_s(E,\mu) P_l(\mu) d\mu$$

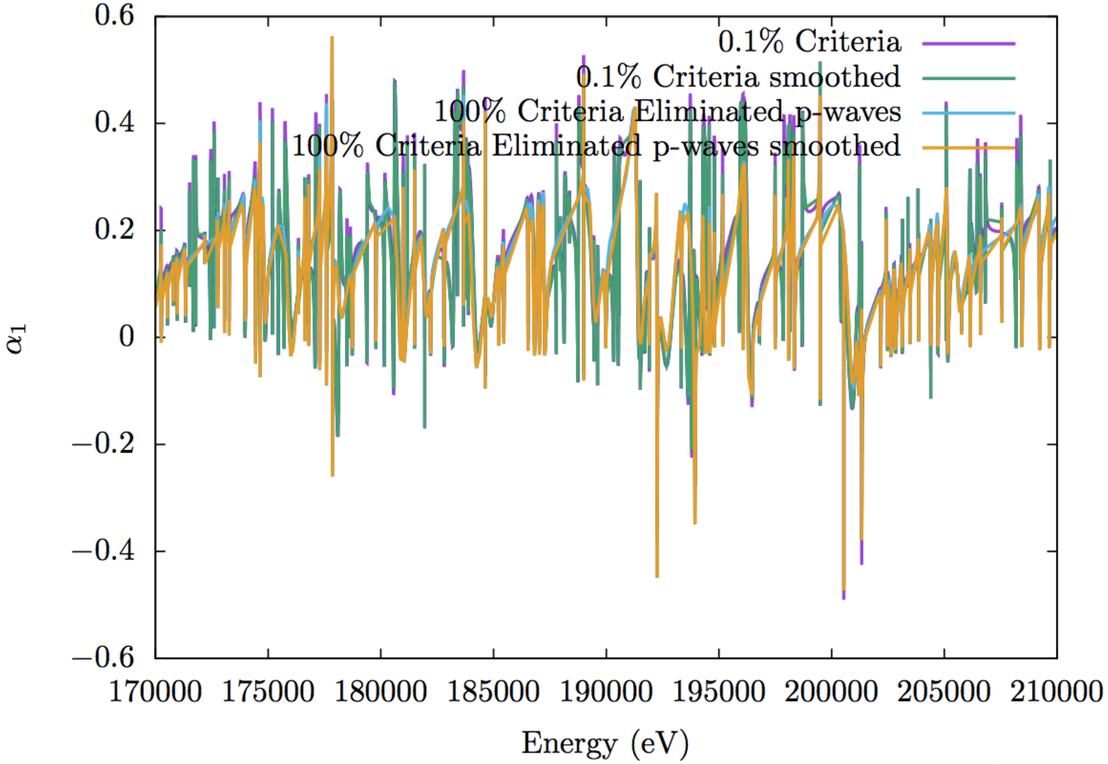
- $P_1(\mu) = \mu$
- $P_2(\mu) = 3/2\mu^2 - 1/2,$

Smoothing of Angular Distributions: Joint effort with Luiz Leal (IRSN)



Interpolation Criteria	^{63}Cu		^{65}Cu	
		Smoothed		Smoothed
0.1%	83 467	10 373	65 922	7 943
10%	16 673	8 568	14 119	6 805
100%	11 440	7 078	10 341	5 758

Smoothing of Angular Distributions: Joint effort with Luiz Leal (IRSN)



Interpolation Criteria	^{63}Cu		^{65}Cu	
	10%	100%	10%	100%
Eliminated p-waves	8 624	5 409	6 080	4 089
Eliminated p-waves (smoothed)	3 543	2 711	2 245	1 769
Eliminated p-wave, Reduced s-waves	5 366	2 756	3 417	1 850
Eliminated p-wave, Reduced s-waves (smoothed)	2 442	1 762	1 555	1 151

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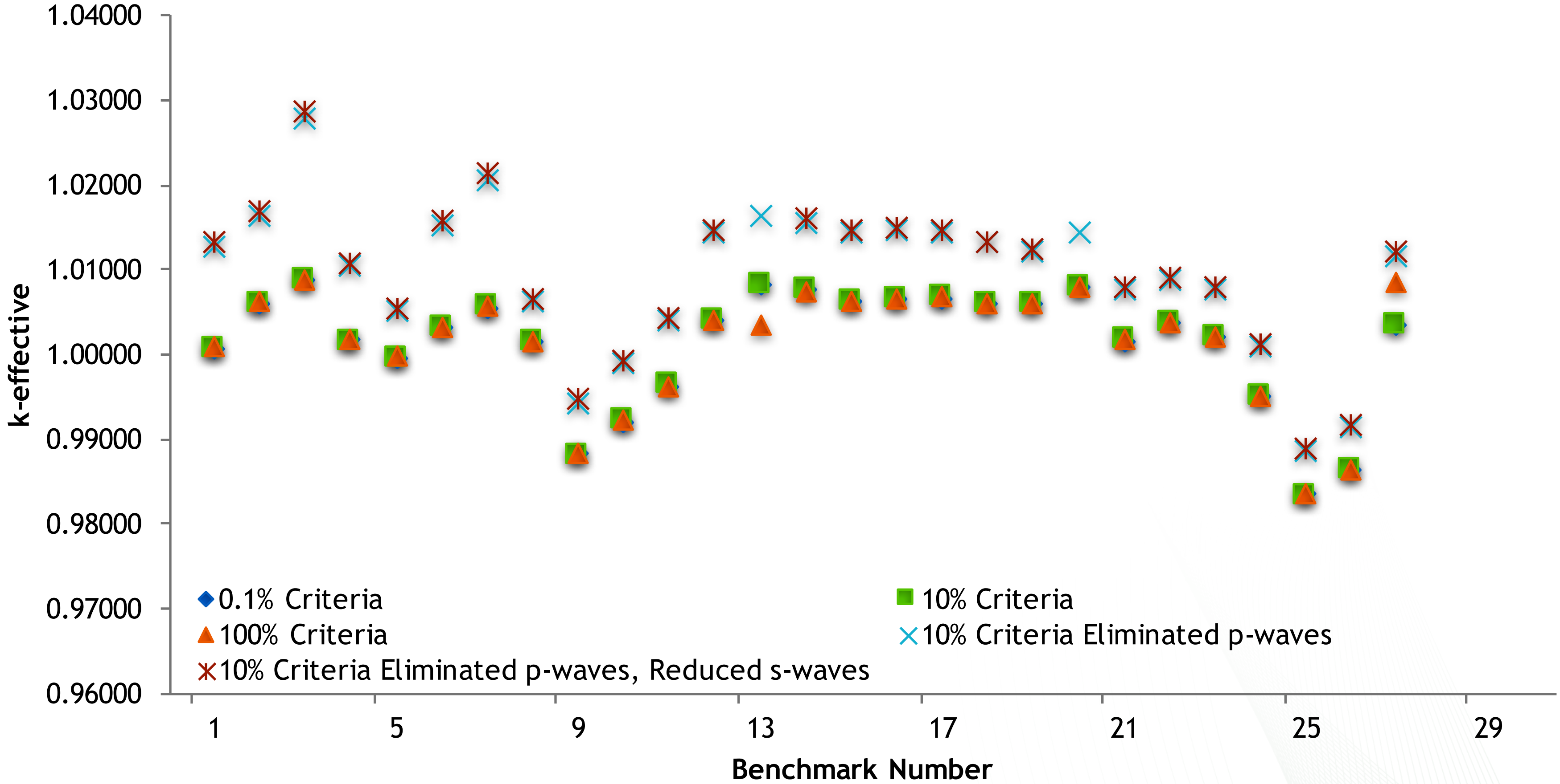
Benchmark Results with Varying Fidelity of Angular Distributions

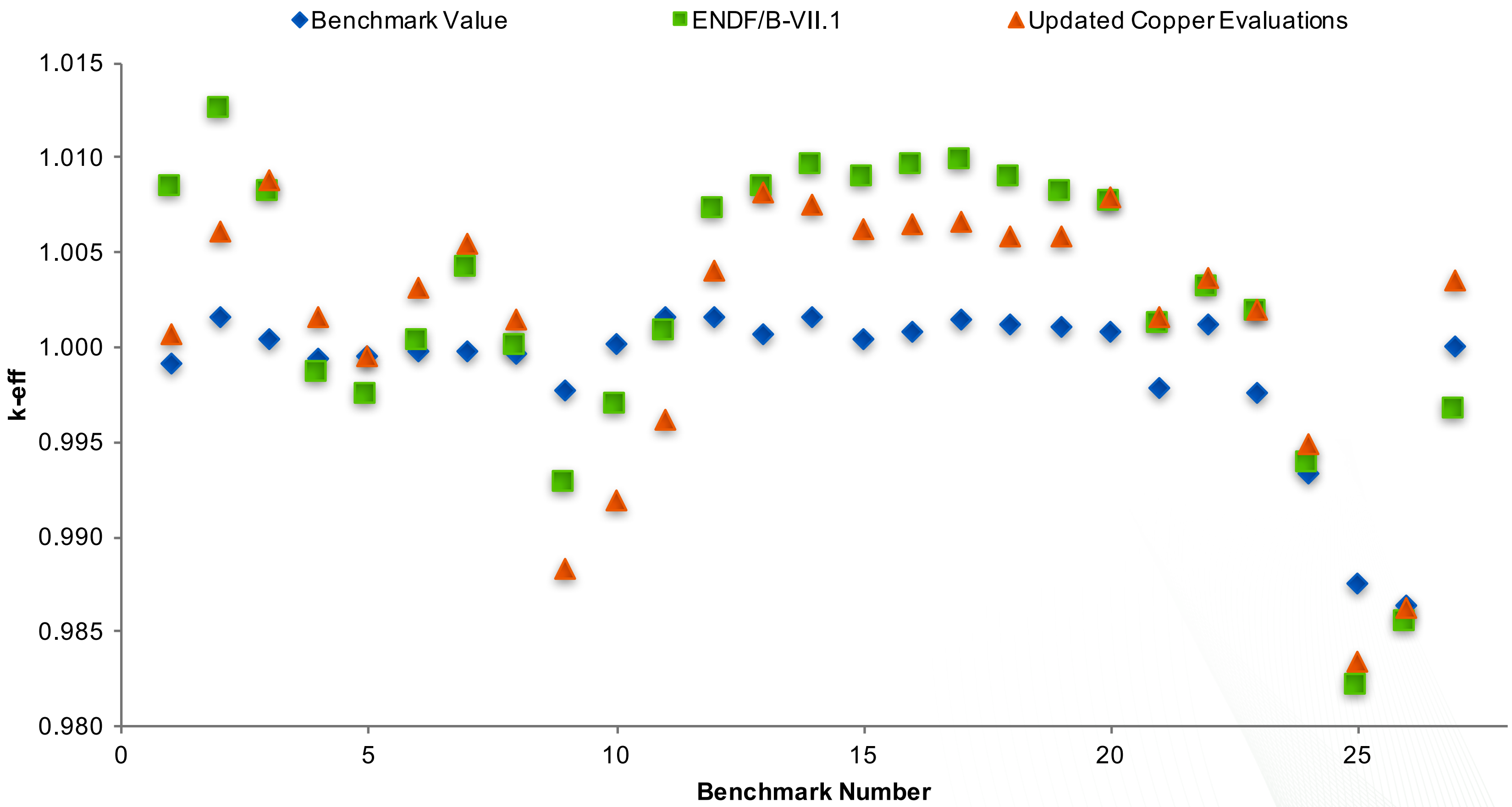


Benchmark Table

Benchmark Number	ICSBEP Benchmark Name
1	HMF-72-01
2	HMF-72-03
3	HMF-73-01
4	HMF-84-06
5	HMF-84-18
6	HMF-85-01
7	HMF-85-02
8	HMF-85-04
9	HMI-06-01
10	HMI-06-02
11	HMI-06-03
12	HMI-06-04
13	IMF-20-01

Benchmark Number	ICSBEP Benchmark Name
14	IMF-20-02
15	IMF-20-03
16	IMF-20-04
17	IMF-20-05
18	IMF-20-06
19	IMF-20-07
20	IMF-22-01
21	IMF-22-05
22	IMF-22-06
23	IMF-22-07
24	IMI-01-02
25	IMI-01-03
26	IMI-01-04
27	PMF-40-01

Overall Benchmark Results



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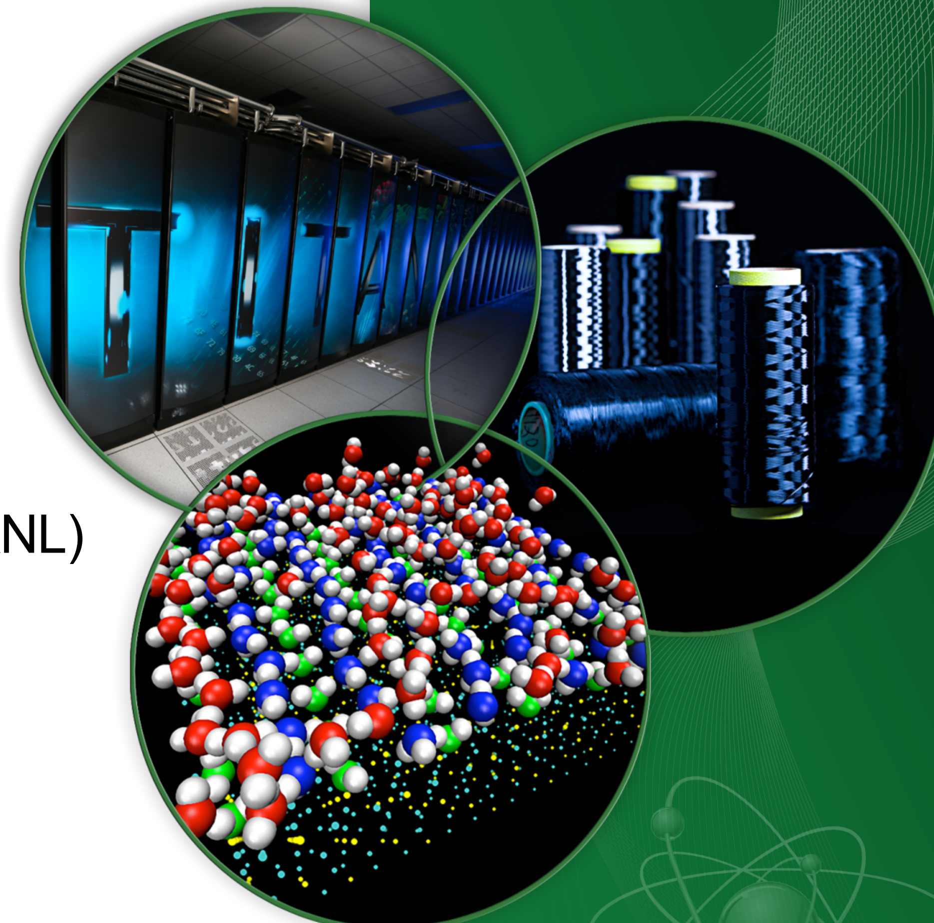
Conclusions

- Resolved Resonance Region Evaluations of ^{63}Cu and ^{65}Cu:
    1. Experimental thermal cross section measurement
    2. Resolved resonance region extended 3 x
    3. Experimental capture data analyzed
    4. High fidelity angular distribution generated

- Improvements for the ^{63}Cu and ^{65}Cu Resonance Evaluations
    1. Updated Capture Cross Section E > 220 keV
    2. Reduced storage requirements for high fidelity angular distributions
    3. Benchmarked updated evaluations

Improvements for the ^{63}Cu and ^{65}Cu Resonance Evaluations for Criticality Safety Applications



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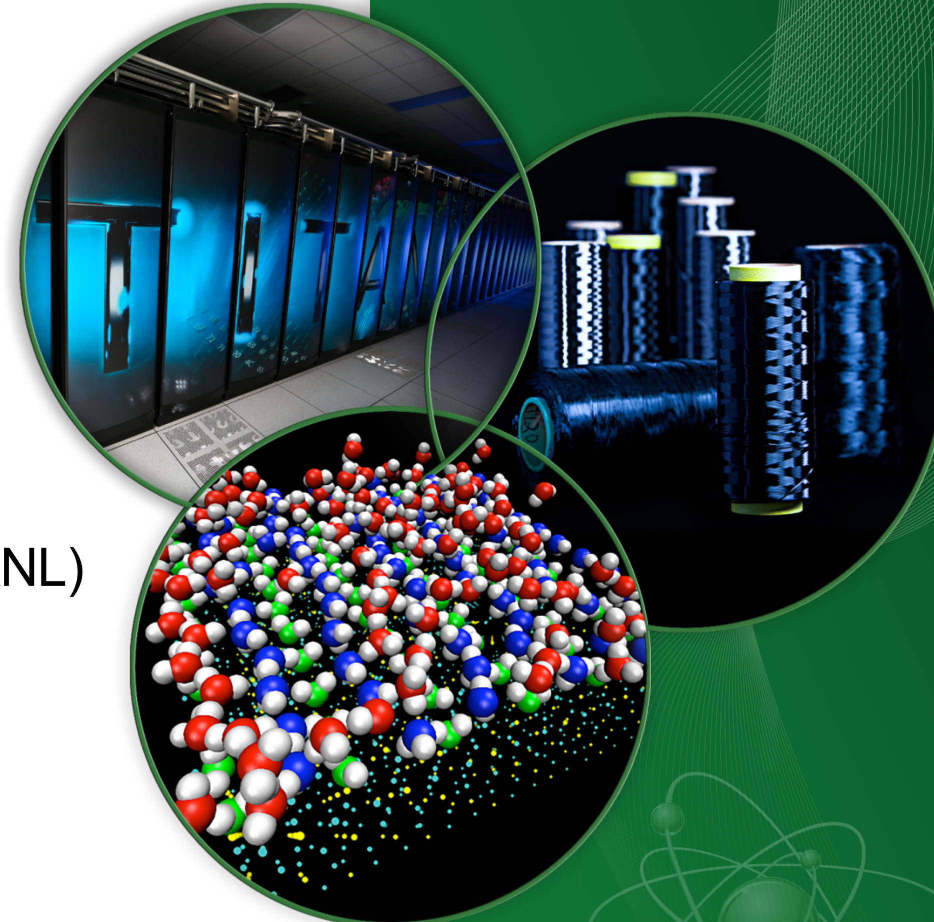
Improvements for the ^{63}Cu and ^{65}Cu Resonance Evaluations for Criticality Safety Applications

Appendix Slides



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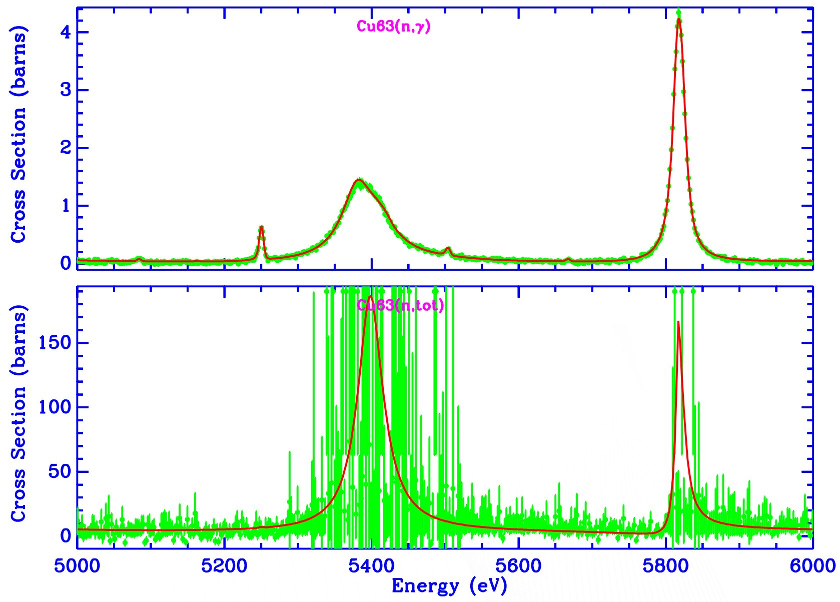
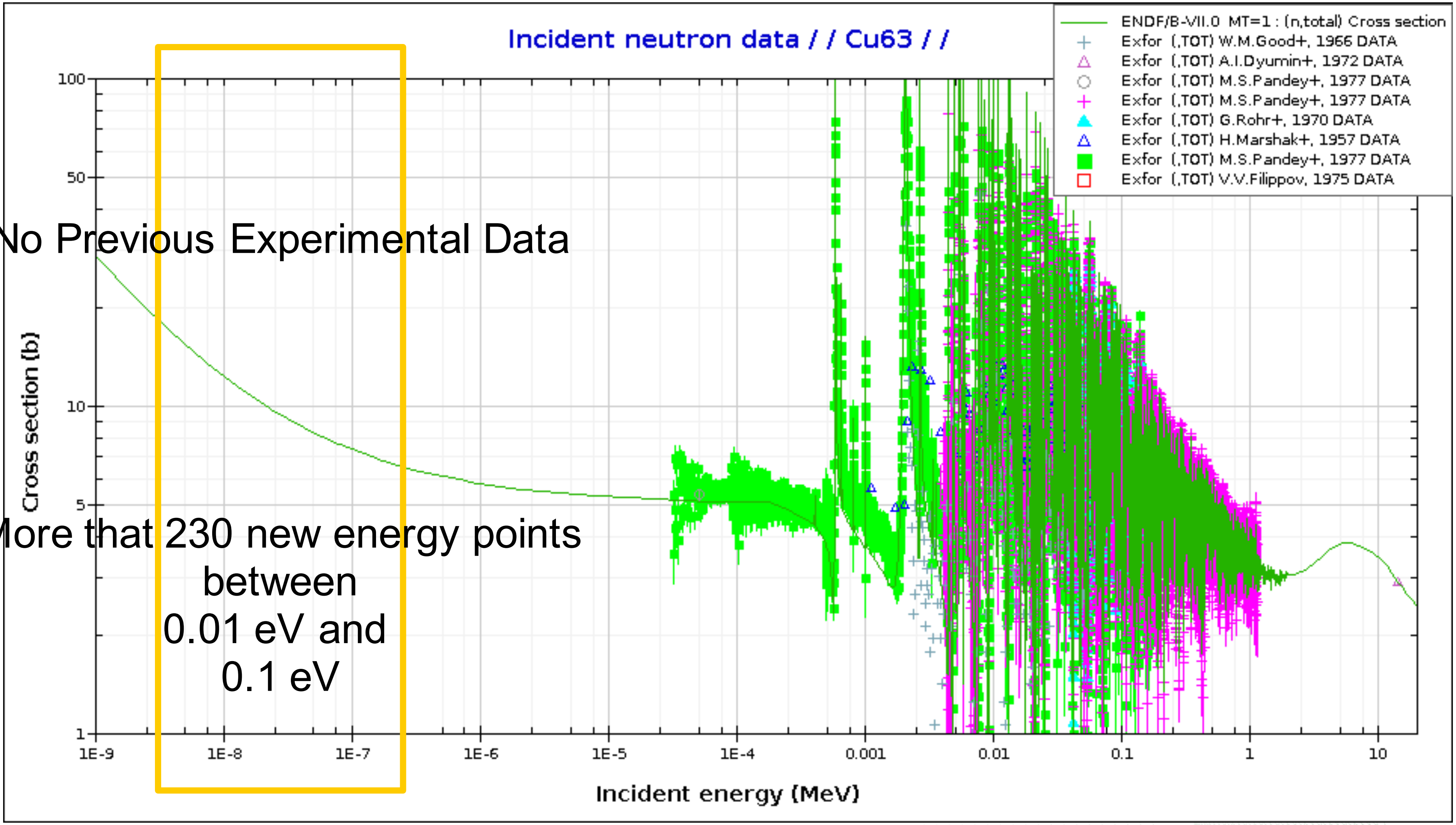
Resolved Resonance Region Evaluations

- Evaluate experimental data with R-Matrix model of nuclear reactions to find optimal model parameters:
- Resonance Energy, E_{λ}
- Neutron Width, $\Gamma_{n,\lambda}$
- Gamma Width, $\Gamma_{\gamma,\lambda}$ (single value for each nucleus)
- Quantum Angular Momentum (determines shape of resonance)



Prior Experimental Data

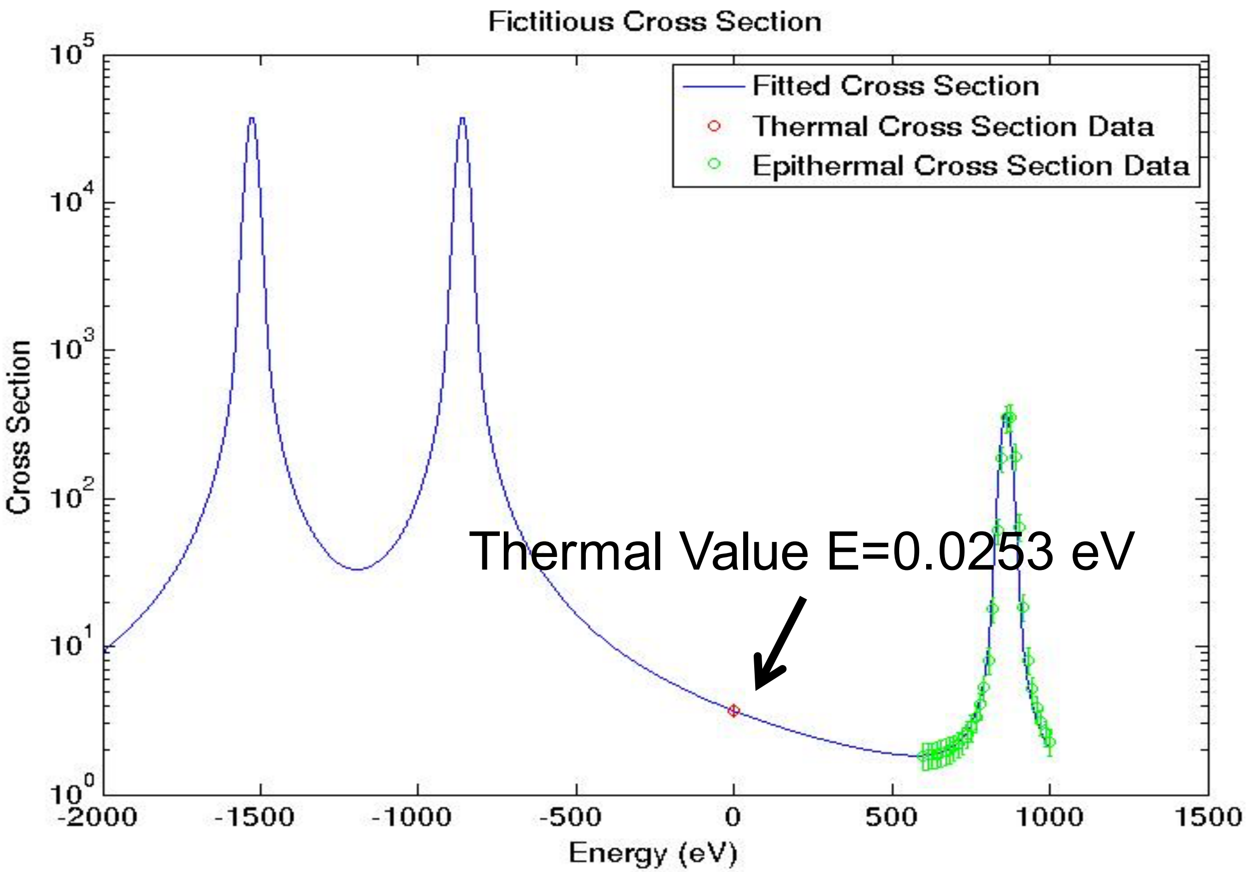


No Previous Experimental Data

More that 230 new energy points between 0.01 eV and 0.1 eV

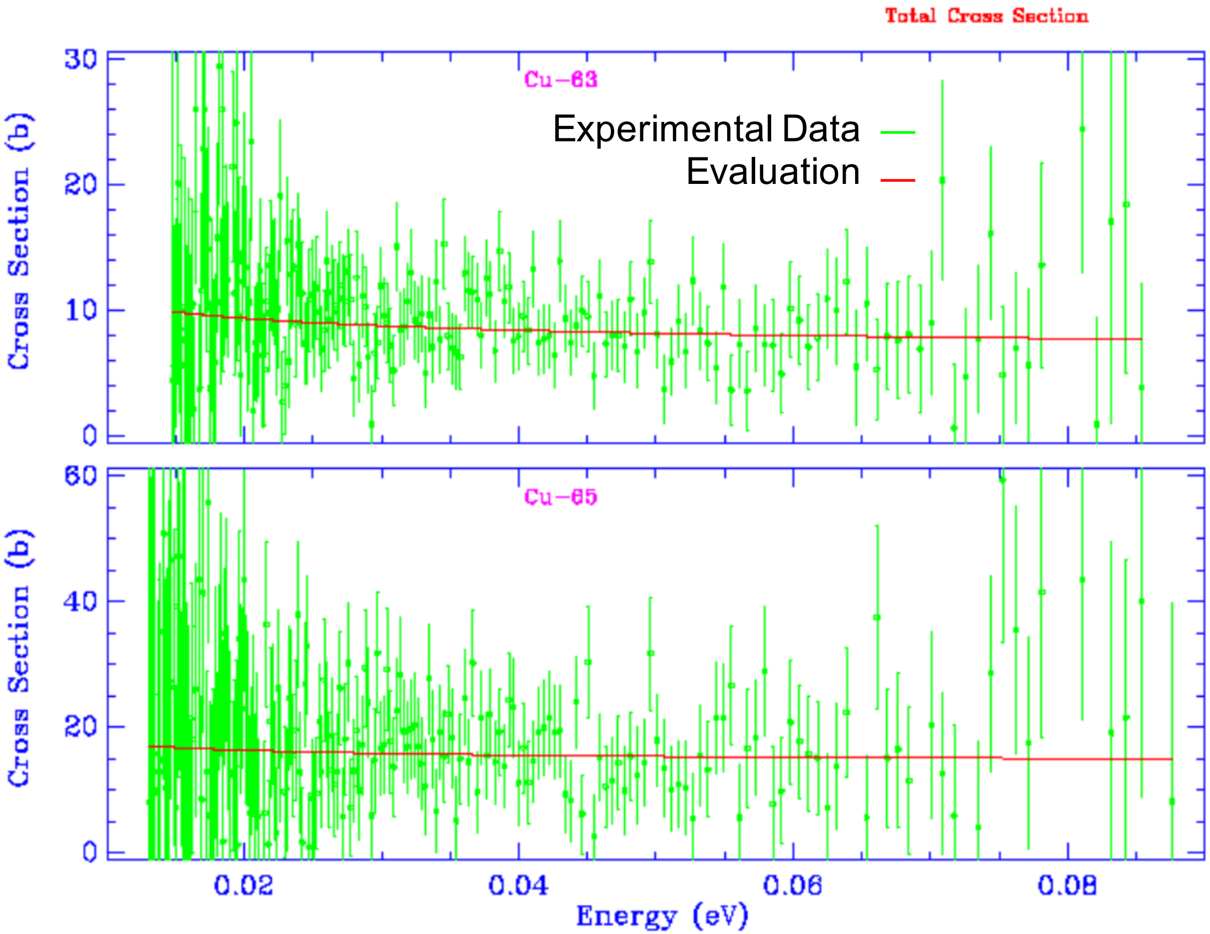
Negative External Levels

- Use the best approximation of the negative external levels?



A lot of freedom in selecting external levels if we have to fit only one point

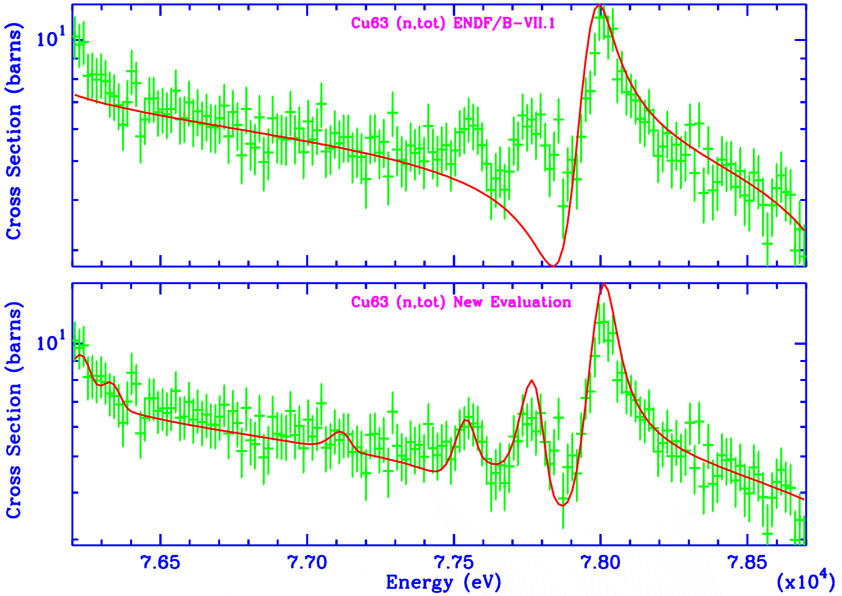
Results



Total Cross Section
Cu-63
Experimental Data
Evaluation
Cross Section (b)
30
20
10
0
Cu-65
60
40
20
0
0.02
0.04
0.06
0.08
Energy (eV)

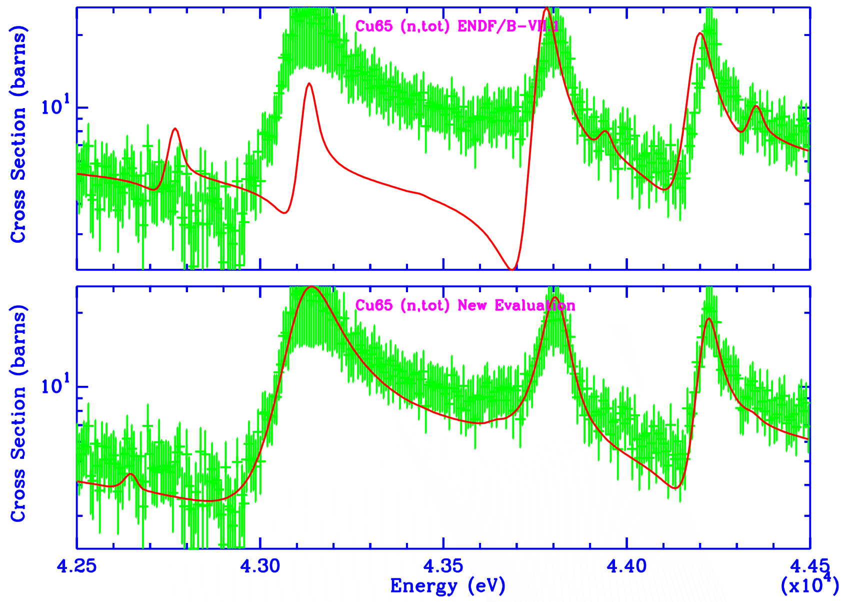
ENDF/B-VII.1 (top) vs. New Evaluation (bottom) 63Cu (n,tot)

- Experimental data plotted for both is identical
- This experimental data was available for the ENDF/B-VII.1 evaluation



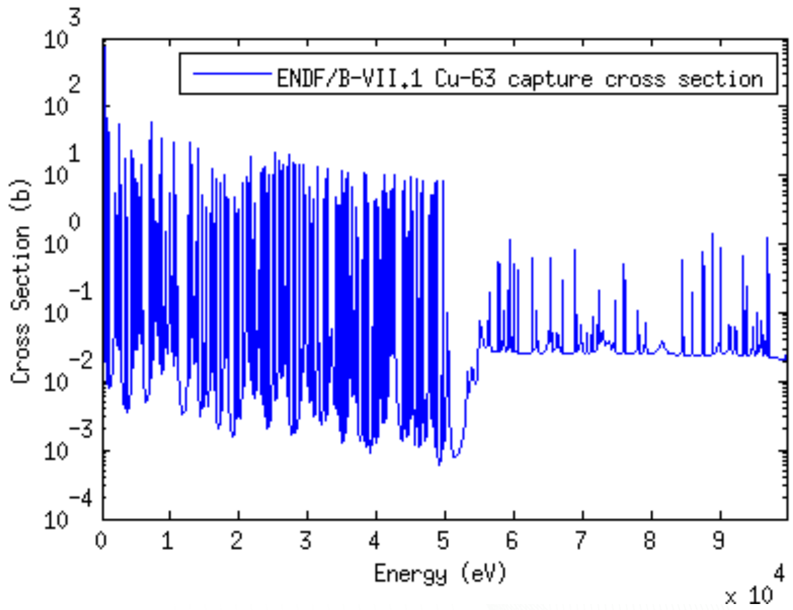
ENDF/B-VII.1 (top) vs. New Evaluation (bottom) 65Cu (n,tot)

- Experimental data plotted for both is identical
- This experimental data was available for the ENDF/B-VII.1 evaluation
- Note the magnitude of the uncertainty in the experimental data



ENDF/B-VII.1 Evaluation for 63Cu and 65Cu

- No capture experimental data available
- A constant background added to the capture data



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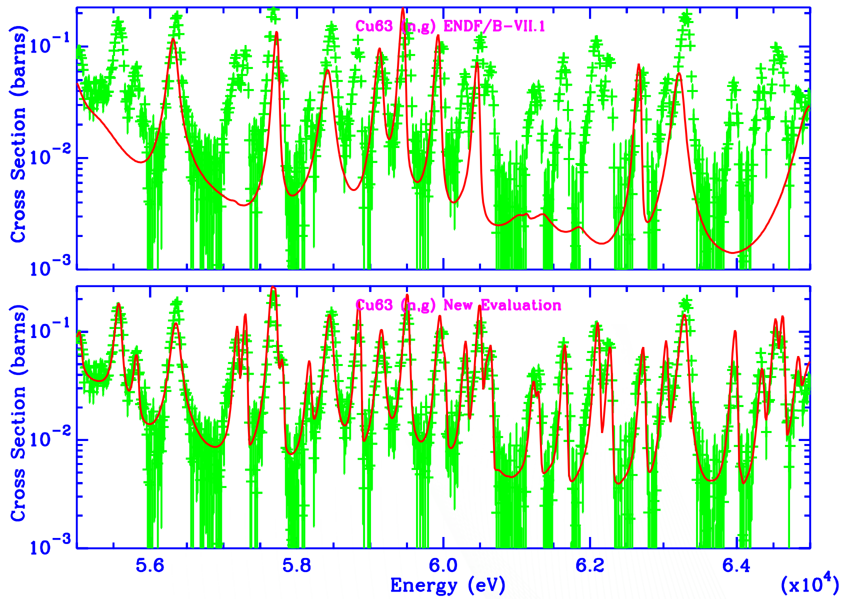
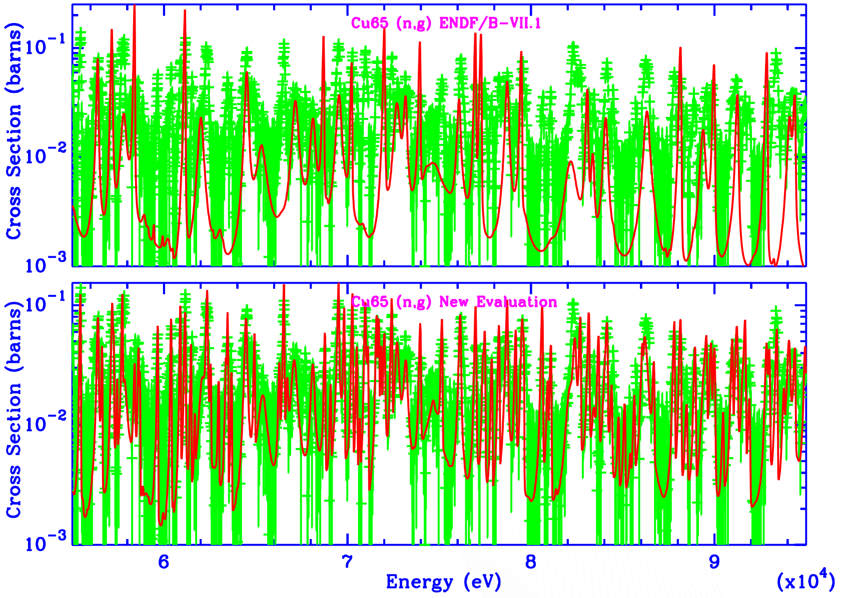
ENDF/B-VII.1 (top) vs. New Evaluation (bottom) 63Cu (n,γ)

- Experimental data plotted for both is identical
- This experimental data was not available for the ENDF/B-VII.1 evaluation

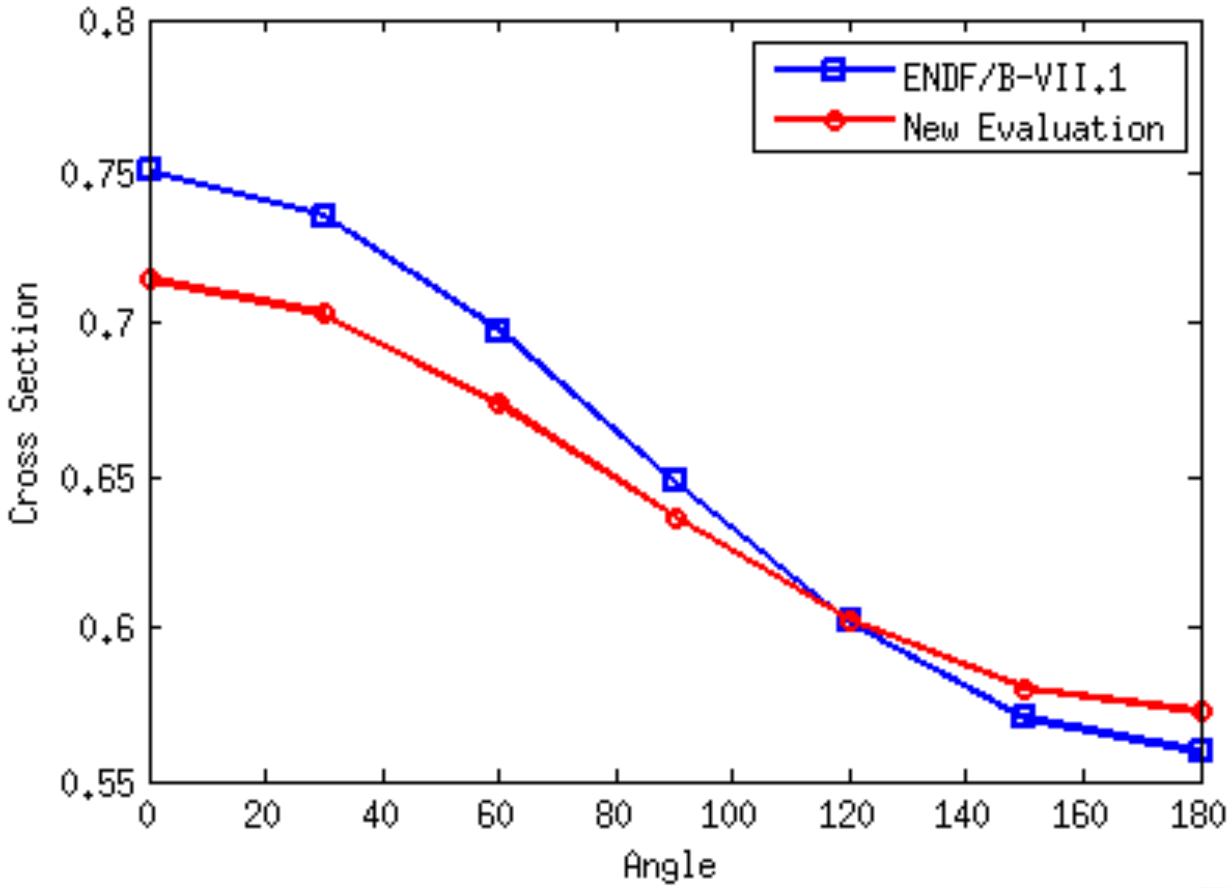


ENDF/B-VII.1 (top) vs. New Evaluation (bottom) 65Cu (n,γ)

- Experimental data plotted for both is identical
- This experimental data was not available for the ENDF/B-VII.1 evaluation



New Differential Scattering Cross Sections Generated

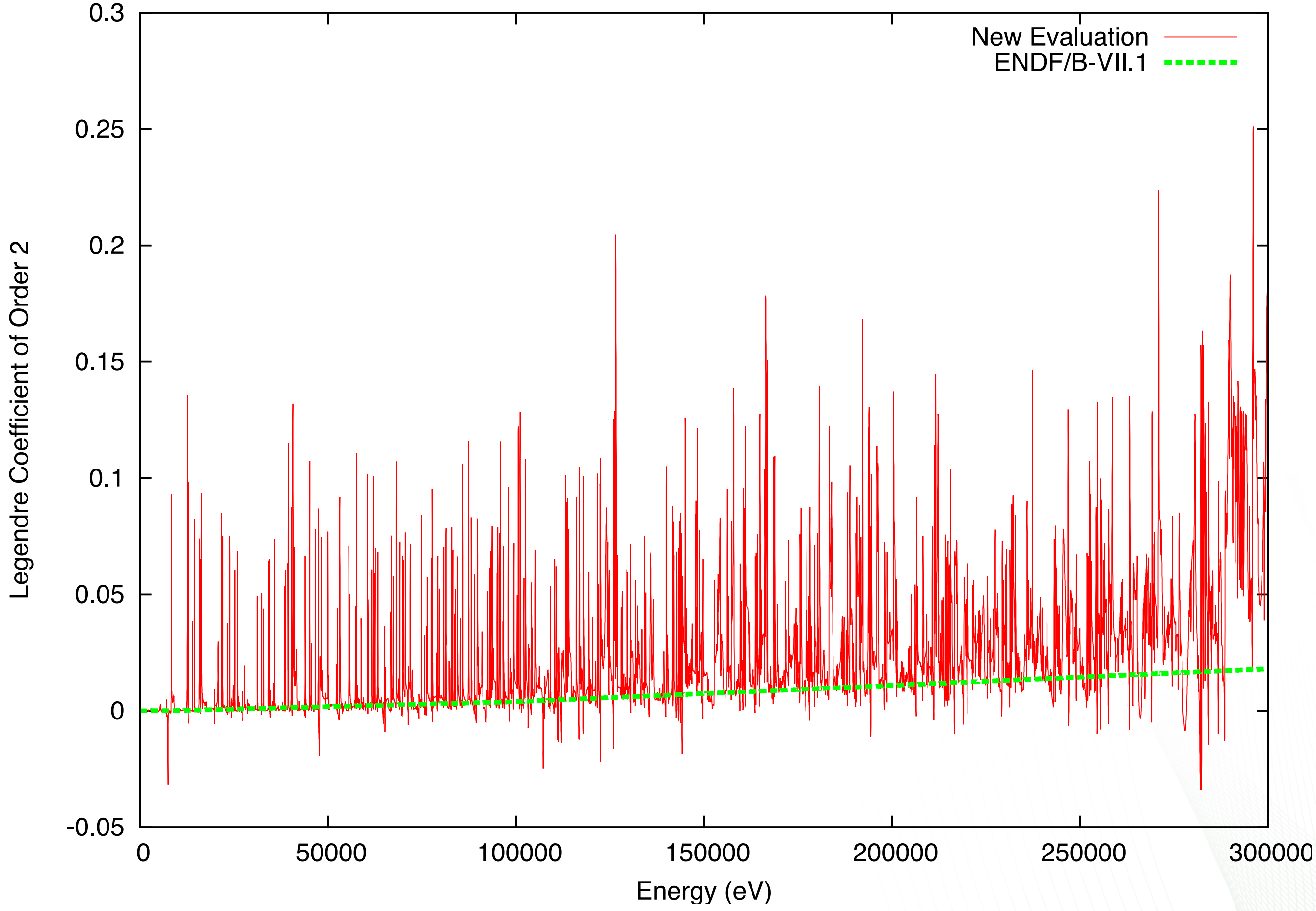


Differential cross section with respect to angle at E=60 keV for 63 Cu(n,els)

Angular Distribution Definitions

- Angle-integrated scattering cross section
  - $\sigma_s(E)$ - A measure of the probability of a scattering event occurring for a given incident neutron energy, E.
- Differential scattering cross section with respect to angle
  - $\sigma_s(E,\mu)$ - A measure of the probability of a scattering event occurring for a given incident neutron energy, E, and resulting in the outgoing neutron traveling in a direction defined by μ. Where, μ, is the cosine of the angle between the incident and outgoing neutron.

High Fidelity Model of Angular Distributions
^{63}Cu (n,els) α_2(E) - Forward/Backward or Side-to-Side Scattering



Average Level Spacing for Different Angular Momenta

^{63}Cu

Angular Momentum	Mughabghab	ENDF/B-VII.1	New Evaluation
s-wave	722+/-47 eV	523+/-53 eV	476+/-42 eV
p-wave	404+/-22 eV	2268+/-775 eV	544+/-65 eV

^{65}Cu

Angular Momentum	Mughabghab	ENDF/B-VII.1	New Evaluation
s-wave	1520+/-100 eV	771+/-83 eV	535+/-42 eV
p-wave	628+/-39 eV	3132+/-360 eV	765+/-84 eV